Title: Acute cardiovascular and ventilatory responses to inspiratory pressure threshold loading

Authors: Alison K McConnell[1] and Lisa A Griffiths[2]

Institutional Affiliations:

[1]Centre for Sports Medicine and Human Performance, Brunel University, Uxbridge, United Kingdom; [2] School of Sport, Leisure and Travel, Buckinghamshire New University, High Wycombe, United Kingdom.

Correspondence:

Professor Alison McConnell

Centre for Sports Medicine & Human Performance

Brunel University

Uxbridge, UB8 3PH

UNITED KINGDOM

Tel: +44 (0)1895 266480

Fax: +44 (0)1895 269769

Email: Alison.mcconnell@brunel.ac.uk

Running Title: Acute responses to inspiratory loading

ABSTRACT

We tested the acute responses to differing pressure threshold inspiratory loading intensities in well-trained rowers. The purpose of this study was to evaluate, 1) how the magnitude of inspiratory pressure threshold loading influences repetition maximum (RM), tidal volume (V_T) and external work undertaken by the inspiratory muscle, 2) whether the inspiratory muscle metaboreflex is activated during acute inspiratory pressure threshold loading. Eight males participated in seven trials. Baseline measurements of maximal inspiratory pressure (P_{Imax}), resting tidal volume (V_T) and forced vital capacity (FVC) were made. During the remaining six sessions, participants undertook a series of resistive inspiratory breathing tasks at loads corresponding to 50%, 60%, 70%, 80% and 90% of P_{Imax} using a pressure threshold inspiratory muscle trainer. The number of repetitions completed at each load, V_T, heart rate and measures of arterial blood pressure were assessed continuously during each trial. A standardised cut-off of 10% FVC was used to define the RM, which decreased as loading intensity increased ($P < 0.05$). This response was non-linear, with an abrupt decrease in RM occurring at loads $\geq$ 70% of P_{Imax}. The most commonly used IMT regimen of 30RM corresponded to 62.5 ± 4.63% of P_{Imax}, and also resulted in the highest external work output Tidal volume (V_T) decreased significantly over time at 60%, 70% and 80% of P_{Imax} ($P < 0.05$), as did the amount of external work completed ($P < 0.05$). Although all loads elicited a sustained increase in f_c, only the 60% load elicited a sustained rise in MAP ($P = 0.016$) and DBP ($P = 0.015$) and SBP ($P = 0.002$), providing evidence for a metaboreflex response at this load.

Keywords: respiratory muscle loading, repetition maximum

INTRODUCTION

Paragraph Number 1 A number of studies have now shown that moderate intensity (50-60% of maximal inspiratory pressure) pressure threshold inspiratory muscle training (IMT) improves inspiratory muscle strength, power and endurance (16). Accompanying these changes in inspiratory muscle function are improvements in exercise tolerance in healthy young athletes (15), and in patients with respiratory (6) and cardiovascular (4) disease. Furthermore, recent evidence points to attenuation of the inspiratory muscle metaboreflex as an important mechanism underlying post-IMT improvements in exercise tolerance (3, 14, 23).

Paragraph Number 2 The inspiratory muscle metaboreflex has typically been examined using flow resistive loading, and its activation is manifest as a time-dependent increase in mean arterial blood pressure (MAP) and heart rate (f_c) (14, 18, 19, 23). However, it is unclear whether the metaboreflex is activated during acute inspiratory pressure threshold loading (of the type employed during IMT), or indeed, whether this is an obligatory stimulus to the adaptations that result in changes to activation of this reflex following pressure threshold IMT.

Paragraph Number 3 One of the unique features of pressure threshold loading is its fixed magnitude, flow independent, load. Whilst this characteristic offers advantages in terms of the reliability of the training stimulus, it is not without its drawbacks, the principal of which is the interaction of the fixed load with the inspiratory muscle length-tension relationship. This interaction is such that, the greater the magnitude of the inspiratory pressure threshold load, the smaller the tidal volume excursion that can be achieved. Thus, not only do higher loads result in a smaller number of repetitions to task failure, they may also be associated with a reduction in the amount of external work undertaken by the inspiratory muscles. The latter may have important implications for the design of IMT protocols, since there may be a minimum amount of inspiratory work required in order to elicit the changes in function that underpin increases in the metaboreflex threshold.

Paragraph Number 4 Thus, the purpose of this study was to characterise the acute physiological responses to pressure threshold loading across a range of inspiratory loads. Specifically, we sought to evaluate, 1) how the magnitude of the inspiratory pressure threshold load influences repetition maximum, tidal volume and inspiratory muscle work; 2) whether the inspiratory muscle metaboreflex is activated during acute inspiratory pressure threshold loading.

METHODS

Participants.

Paragraph Number 5 Eight healthy competitive male rowers volunteered to participate in this study, which was approved by the Brunel University Research Ethics Committee. Prior to testing, all participants completed a health questionnaire and gave written, informed consent.

Paragraph Number 6 Participants were requested to maintain their normal diet in the few days that preceded testing. Participants were also requested to avoid alcohol and vigorous exercise two days prior to testing and to avoid caffeinated beverages on test day. To minimise the effects of inspiratory muscle fatigue (IMF), participants were limited to one test session per day.

General design.

Paragraph Number 7 Each participant attended seven testing sessions. During session 1, maximal inspiratory mouth pressure (P_{Imax}), resting tidal volume (V_T) and forced vital capacity (FVC) were assessed. During the subsequent six sessions, participants undertook a series of loaded breathing tasks at six loads (50%, 60%, 70%, 80% and 90% of P_{Imax}) using a pressure threshold inspiratory muscle trainer. Participants breathed against each load to the limit of tolerance (T_{lim}) at a breathing frequency of 15 breaths per minute, which was paced by metronome. Ventilatory and cardiovascular responses were monitored throughout each breathing task.

Participant characteristics.

Paragraph Number 8 Stature, body mass and respiratory function were assessed at session 1 and are presented in Table 1.

Inspiratory warm-up.

Paragraph Number 9 Prior to inspiratory muscle strength testing, participants were instructed on proper usage of the pressure threshold-loading device for the inspiratory 'warm-up' (POWERbreathe®, HaB International Ltd., Southam, UK). Participants were instructed to perform 2 sets of 30 breaths at a resistance equivalent to 40% P_{Imax}. This protocol has been shown to attenuate the effect of repeated measurement upon P_{Imax} and to improve reliability (13, 21).

Inspiratory muscle strength.

Paragraph Number 10 Maximal inspiratory pressure was assessed using a portable hand held mouth pressure meter (Morgan Medical, UK). The assessment of P_{Imax} required a sharp, forceful effort maintained for a minimum of ~2s. The pressure meter incorporated a 1 mm leak to prevent glottic closure (1). Measurements were repeated until three technically acceptable manoeuvres were achieved within 3-5 centimetres of water (cmH_2O); the best of these three was recorded.

Pulmonary function.

Paragraph Number 11 Forced vital capacity (FVC) and loaded breath volumes were assessed using an online computer software package. Participants breathed through a flow meter that employed a differential pressure transducer (BIOPAC MP30, © BIOPAC Systems Inc., Goleta, USA), which measured airflow and computed volume.

Measurement of tidal volume during loaded breathing.

Paragraph Number 12 Participants undertook a series of inspiratory loaded breathing tasks using a pressure threshold training device (POWERbreathe®, HaB International Ltd., Southam, UK). The breathing tasks consisted of loads of 50%, 60%, 70%, 80% and 90% of P_{Imax} performed in randomised order. The participants were requested to undertake each load to the limit of tolerance, but no encouragement was provided during the task, and no indication was provided as to how many breaths they should perform. A metronome was used to regulate breathing frequency to 15 breaths per minute. The target duty cycle was 0.5, but in practice, this ranged from 0.3 to 0.5 due to the inertial properties of the threshold load, and the influence of the force-velocity relationship of the inspiratory muscles. After 15 minutes, any participants who were able to maintain the resistive breathing load were stopped. Participants were not informed of the cut-off time of 15 minutes until they reached that point. All participants were encouraged to perform the tasks to their own limit of tolerance, and not to a target time, or number of breaths. The duration from the onset of the task to the point the participant removed the mouthpiece was termed T_{lim} and is presented in seconds (s).

Paragraph Number 13 Tidal volume (V_T) was measured during each loading task, and was predicted to decline with increasing load and with increasing repetitions (due to the effects of the length-tension relationship and fatigue, respectively). Since the time course of the within-test change in V_T was unknown, an objective V_T threshold was determined retrospectively to define the repetition maximum (RM) for each load. A V_T threshold of 10% of FVC was used to define the RM at each load; breaths occurring after V_T had fallen below 10% FVC were excluded (for RM determination purposes).

Assessment of cardiovascular responses.

Paragraph Number 14 Measures of heart rate (f_c) and arterial blood pressure were made non-invasively during the loaded breathing tasks using an automated combined continuous blood pressure monitor (Colin CBM-7000, Scanmed, UK). Blood pressure was measured using arterial tonometry; a solid-state blood pressure transducer sensor was attached to the participants left wrist over the radial artery. An oscillometric brachial cuff provided calibration for the pressure transducer sensor. Measures of MAP, systolic and diastolic blood pressure (SBP and DBP, respectively) are presented in millimetres of mercury (mmHg). Continuous f_c was recorded and presented as beats per minute (bpm).

Data analysis.

Paragraph Number 15 Temporal data were analysed using two methods. Firstly, to account for differences in the number of repetitions achieved and changes in V_T, each breathing task was divided into isotime quartiles. Secondly, pulmonary and cardiovascular data were also analysed every 30s for the first 3 minutes at loads of 50% and 60% and every 15s for the first minute at loads of 70%, 80% and 90% to determine the onset, if present, of the inspiratory muscle metaboreflex. Mean values were calculated for each outcome variable and subjected to statistical analysis. Participants not achieving 4 breaths for a given task were excluded from the analysis at that particular load. In addition, an approximation of inspiratory work was made to determine if the combination of load and volume resulted in more or less external work at any given inspiratory load. Average work per breath was calculated for each resistive load using the following equation:

Work = force [pressure] x distance [volume]

Inspiratory Work = inspiratory threshold load (cmH_2O) x V_T (L)

Paragraph Number 16 A repeated measures analysis of variance (ANOVA) was used to determine physiological changes over time. Planned pairwise comparisons were made to analyse significant interaction effects using the Bonferroni adjustment. Pearson's correlation coefficients were performed to determine relationships between physiological and performance variables. Probability values $\leq$ 0.05 were considered significant. Statistical and mean data were calculated using the statistical software SPSS V16.0 for Windows (SPSS Inc, Chicago, IL, USA). All results are expressed in mean ± SD unless stated otherwise.

RESULTS

Repetition maximum at each load.

Paragraph Number 17 Data for average total number of repetitions, the number of repetitions performed at a V_T > 10% FVC threshold load, and average T_{lim} at each load are presented in Table 2. There was a statistically significant within-participant effect for the total number of breaths (P = 0.001; Greenhouse-Geisser), indicating a difference in the number of repetitions performed at differing loads. As shown in Table 2, there was a statistical difference between total repetitions performed at 50% P_{Imax} compared to 70% (P = 0.011), 80% (P = 0.009) and 90% (P = 0.010). Similarly, when the objective V_T criterion was applied to determine RM, there was a statistical difference within participants (P = 0.001; Greenhouse-Geisser) at 50% compared to 70% (P = 0.013), 80% (P = 0.010) and 90% (P = 0.011).

Paragraph Number 18 Participants completed the various breathing tasks at different time points. As shown in Table 2, there was an abrupt drop in T_{lim} at loads >70% P_{Imax}. During the 50% and 60% loads, there were a few participants (n=3 and n=2, respectively) who maintained the task to the 15 minutes cut off point. On average, the 30RM corresponded to 62.5 ± 4.63 % P_{Imax} (60% in six participants and 70% in two).

Paragraph Number 19 Significant correlations were found between FVC and the number of repetitions completed at 70% P_{Imax} (r = 0.806; P = 0.016) and 90% P_{Imax} (r = 0.841; P = 0.009). Although these relationships were significant, this significance was due primarily to one or two outliers. There were no significant correlations between the number of repetitions performed and stature, body mass, V_T, or P_{Imax} at any load.

Within task changes in tidal volume and tidal volume expressed as a percent of forced vital capacity.

Paragraph Number 20 Significant differences were detected in V_T between participants at 60% (P = 0.039) and within-participants over time at 50% (P = 0.023), 60% (P = 0.006), 70% (P = 0.041) and 80% (P = 0.000; see Table 3). No analysis was performed for the 90% load, as insufficient participants (n=2) were able to sustain breathing above the 10% FVC tidal volume threshold. When tidal volume was expressed as a percentage of FVC (V_T%FVC) there was also a significant within-participant effect at 60%, 70% and 80% (P < 0.05), but not at 50%.

Estimation of average external work.

Paragraph Number 21 There was a significant within-participant effect over time (P = 0.006; Greenhouse-Geisser) when comparing the estimated average work completed at each load (see Figure 1). Estimated average work was highest during the 60% load compared to 50% (13.6% difference; P = 0.012), 70% (22.5% difference; P = 0.023) and 80% (40.6% difference; P = 0.043). Inspiratory work undertaken at all loads was highest within the first quartile, decreasing progressively over time at all loads (P < 0.05). Bivariate correlations were performed to compare the relationship between average work completed to average f_c at each load and to the number of repetitions at each load; no significant correlations were found at any load.

Cardiovascular response.

Paragraph Number 22 Because of the large reduction in the number of repetitions completed at loads ≥70% P_{Imax} (see table 2), differing temporal analyses were undertaken for data below and ≥70% P_{Imax}. Analysis of loads at 50% and 60% P_{Imax} were undertaken at 30s bin intervals for the first three minutes of loading. Loads ≥ 70% P_{Imax} were analysed at 15s bin intervals for the first minute, as some participants were unable to maintain breathing for more than 30s.

Temporal analysis of the cardiovascular response at 50% and 60% P_{Imax}.

Paragraph Number 23 Repeated measures ANOVA did not reveal any significant differences between loads for MAP (P = 0.343), SBP (P =0.314) or DBP (P = 0.313); however there was a clear and sustained difference in blood pressure between the 60% and 50% loads (see Table 4 and Figure 2A to C). Therefore, planned pairwise comparisons were undertaken, with Bonferroni correction, to determine if there were any significant changes within-loads (P set at ≤ 0.016) and between-loads (P set at ≤ 0.025) at the 30s, 60s and 90s time intervals compared to baseline. Comparisons were not made beyond 90s because of the decreasing number of participants able to sustain the 60% load beyond this time point. Using the critical P values above, there was a significant increase from baseline to the 60s time interval in MAP (P = 0.016) and DBP (P = 0.015) at the 60% load. The 60% load also elicited a rise in SBP from baseline to the 60s (P = 0.002) and 90s (P = 0.002) time interval; furthermore, there was a significant difference in SBP at the 30s time interval compared to the 50% load (P = 0.020). No change in blood pressure was evident over time during the 50% load.

Paragraph Number 24 Repeated measures ANOVA revealed a significant between participant (P = 0.002) and within-participant effect (P = 0.001) over time for f_c when comparing the 50% and 60% load. Heart rate also exhibited a sustained increase from baseline during the 60% (P = 0.000) load. Pairwise comparisons with Bonferroni correction (P set at $\leq$ 0.016) revealed significant differences at 30s (P = 0.013), 60s (P = 0.015) and 90s (P = 0.002) time intervals compared to baseline during the 50% load (Figure 2D).

Paragraph Number 25 Whilst there were no significant differences in average work completed at the 50% and 60% loads (P = 0.262), the average work completed during the first 2 minutes at the 60% load was 10.7% higher (255.4 ± 12.9 cmH_2O.L) compared to that at 50% (228.4 ± 9.1 cmH_2O.L). No statistical analysis was performed from 120s to 180s due to the small number of participants (n=4) able to continue the task for 3 minutes at the 60% load.

Temporal analysis of the cardiovascular response at loads ≥70%.

Paragraph Number 26 Only those participants able to complete at least 30s of breathing were included in the temporal analysis at loads ≥70%. Table 5 compares the cardiovascular responses at 15s intervals for loads of 70%, 80% and 90%. Although there was a significant within participant effect for all variables (P < 0.05), there were no significant differences between loads. All loads elicited a significant increase in f_c over time compared to baseline (P < 0.05), but planned pairwise comparisons revealed no significant changes in any other cardiovascular variable.

DISCUSSION

Paragraph Number 27 The purpose of this study was to characterise the acute physiological response to a range of pressure threshold inspiratory loads. To this end, all participants undertook loaded breathing tasks at loads ranging from 50-90% P_{Imax} during which ventilatory and cardiovascular responses were assessed. As expected, T_{lim} decreased as loading intensity increased, but this response was non-linear, with an abrupt decrease in T_{lim} at loads ≥ 70% P_{Imax}. Estimated external work was greatest at the 60% load and lowest at the 80% load. Although all loads elicited a sustained increase in f_c, only the 60% load elicited a sustained rise in SBP and MAP, providing evidence for a metaboreflex response at this load.

Load magnitude and repetition maximum.

Paragraph Number 28 There was little difference between the total number of repetitions completed to task failure and the number of repetitions defined objectively using the V_T%FVC threshold (see Table 2). At 50% and 60% P_{Imax}, participants were able to complete an average of 134 ± 68 repetitions (537 ± 268 sec), and 85 ± 85 repetitions (339 ± 342 sec), respectively. Direct comparison with previous studies employing flow resistive inspiratory loading is problematic, since not only did the method of loading differ in the present study, but also the breathing frequency, duty cycle (15 breaths per min and 0.5, respectively in the present study) and tidal volume. For example, Witt *et al.* (23) observed that T_{lim} during inspiratory flow resistive loading at 60% P_{Imax} occurred after 535 ± 52 sec, which corresponded to ~133 repetitions at their breathing frequency of 15 breaths per min and duty cycle of 0.7. On the face of it, the tolerance to moderate (60% P_{Imax}) inspiratory flow resistive loading appears much greater than to pressure threshold loading. However, V_T in the Witt *et al.,* (23) study was less than half that of the present study (~1 l *vs.* ~2 l, respectively), reducing the external work associated with each breath. In addition, the inertial properties of a pressure threshold load tend to lead to higher inspiratory flow rates and a reduction in inspiratory time (5), despite the imposed duty cycle. In theory, the associated reduction in duty cycle should reduce the likelihood of fatigue of the inspiratory muscles, but in practice, the higher inspiratory flow rate increases the relative load upon the inspiratory muscles due to functional weakening at higher velocities of shortening (12). These factors may collectively hasten T_{lim} during pressure threshold loading, compared with flow resistive loading.

Paragraph Number 29 There was a non-linear, inverse relationship between the number of repetitions completed and the magnitude of the inspiratory load. The break point of this relationship occurred at the 70% P_{Imax} load (see Table 2). Our results showed a broadly similar relationship between relative inspiratory muscle load and number of repetitions to that of limb muscles, in that participants performed an average of 1-7 repetitions at training loads > 80% P_{Imax}, 7-17 repetitions between 70-80% P_{Imax} and >18 repetitions at loads ≤ 60%. In traditional whole body resistance training, loads > 80-85% of the one repetition maximum (1RM) are typically associated with regimens of 1-6 repetitions, loads of 70-80% 1RM with ~6-12 repetitions, and loads of ≤ 60% 1RM with 12-15 repetitions (11). Our data suggest that the relationship between relative load and the number of repetitions to task failure is similar to limb muscles at high loading, but that the ability to tolerate low to moderate loads may be greater for the inspiratory muscles, e.g., 84 repetitions at 60% P_{Imax}, compared with 12-15 repetitions for whole body resistance training at a similar relative load. This may be a reflection of the more aerobic phenotype typical of inspiratory muscles (7), as well as the absence of an eccentric phase to the inspiratory muscle loading.

Paragraph Number 30 Previous studies of pressure threshold IMT in healthy young people have typically utilised loads equivalent to the 30RM (2, 8, 9, 14, 17, 20, 22). Our participants showed marked differences in their individual tolerance to inspiratory loading (see Table 2). For example, at the lowest load of 50% P_{Imax} some participants (n=3) were able to continue to the maximum 15 minute cut off, whereas others reached task failure in less than 4 minutes (n=2). To explore the relationship of the 30RM to the relative P_{Imax} load, we identified the load that induced task failure as close as possible to 30 breaths for each participant, which corresponded to 60% for six participants and 70% for the remaining two. Thus, for our participants, the load most closely corresponding to the 30RM was 62.5% P_{Imax}. Interestingly, a recent study investigating pressure threshold IMT in elite oarsmen (10) showed no IMT-induced change in P_{Imax} using a load of 50% P_{Imax}, whereas they found a significant 21% increase in P_{Imax} following 6 wk of IMT using a load of ~62 ± 3% P_{Imax}. These data suggest that, in trained individuals at least, a pressure threshold load in excess of 60% P_{Imax} is required to elicit improvements in P_{Imax}, and the present data indicate that this can be approximated by using the 30RM.

Tidal volume and external work during pressure threshold loading.

Paragraph Number 31 Participants were instructed to maximise V_T during inspiratory loading in order to explore how loading influenced V_T. It was assumed that the interaction of the fixed pressure threshold load with the length-tension relationship of the inspiratory muscles would influence the starting V_T, and that progressive fatigue would lead to a reduction in V_T during loading. As seen in Table 3, these assumptions were confirmed. However, it is notable that V_T during the 50% and 60% loads was disproportionately larger than that seen at the 70% and 80% loads. We speculate that this may be due to the non-linearity of the length-tension relationship, such that high loads are on a steeper portion of this relationship than moderate loads. Hence, smaller changes in volume result in larger reductions in force generating capacity at higher loads. It appears that the breakpoint for this relationship occurs between 60% and 70% of P_{Imax}. There was also a significant effect of time upon V_T at loads $\geq$ 60% of P_{Imax}. This temporal decline in V_T during flow resistive breathing has been shown previously (18) and is most likely a manifestation of the onset of fatigue. The absence of this phenomenon at the 50% load suggests that loads $\leq$ 50% of P_{Imax} fail to provide adequate overload to the inspiratory muscles in well-trained young men.

Paragraph Number 32 These observations have important implications for the amount of external inspiratory muscle work undertaken at a given load (see figure 1), since external work is the product of the pressure load and the volume change achieved at that load. This was found to decline significantly over time at all loads, and to be significantly greater during the 60% load than at any other load. Counter intuitively, external work was lowest at the 80% load, and this was a direct effect of the lower V_T at this load. During resistance training of limb muscles using inertial loads, external work is a direct function of the external load, since the distance over which the load is moved does not differ between loads, or within a given set. Our data indicate that this is not the case for inspiratory pressure threshold loading. If one accepts the premise that it is desirable to maximise the amount of external work completed, whilst minimising the time taken to achieve this during a given training session, our data suggest that achieving adequate training overload during pressure threshold loading demands a careful balance of maximising load and number of repetitions, whilst minimising the influence of loading upon V_T.

Cardiovascular response to inspiratory resistive loading.

Paragraph Number 33 One of the purposes of this study was to evaluate whether the inspiratory muscle metaboreflex was activated during pressure threshold loading. At the 50% P_{Imax} load there was a significant increase in f_c, but no change in any index of blood pressure, compared to baseline (see Table 4). In contrast, at the 60% P_{Imax} load there was not only an increase in f_c, but also increases in MAP, SBP and DBP, compared to baseline, as well as to the responses at the 50% P_{Imax} load. This observation is consistent with those of both Sheel *et al*. (18) and Witt *et al.* (23) during flow resistive inspiratory loading at 60% P_{Imax}. Both studies observed a time dependent increase in both f_c and MAP within 2-3 minutes of the start of loaded breathing. Our data show an earlier onset of these changes (60s), which have been attributed to activation of the inspiratory muscle metaboreflex, and were only present at the 60% P_{Imax} load.

Paragraph Number 34 Previous studies of the influence of pressure threshold IMT upon the inspiratory muscle metaboreflex threshold have shown that training at loads equivalent to the 30RM (14) and at 50% P_{Imax} for 3 sets of 75 breaths (23), elicit an increase in the threshold for activation of this reflex. Data from the present study suggest that 30RM protocol is associated with the activation of the inspiratory muscle metaboreflex during IMT. In the case of the protocol employed by Witt *et al.* (23), the present study suggests that a continuous set of 134 ± 66.9 breaths at 50% P_{Imax} is insufficient to elicit the metaboreflex. However, it is possible that accumulating at total of 225 breaths (3 x 75 breaths) may be sufficient for activation. Further studies are required in order to identify whether metaboreflex activation during IMT is an obligatory feature of the IMT-induced increase in metaboreflex threshold.

SUMMARY

Paragraph Number 35 The data suggests that there is a non-linear inverse relationship between load magnitude and T_{lim} when breathing against inspiratory pressure threshold loads, and there is large inter-individual variation in tolerance to such loading. In our participants, the 30RM load that has been employed in previous studies of IMT corresponded to a load of 62.5% P_{Imax}. In addition, the length-tension relationship of the inspiratory muscles exerted a potent influence upon V_T during loading, which had a corresponding influence upon the amount of external work undertaken by the inspiratory muscles. Metaboreflex induced increases in indices of arterial blood pressure were evident within 60s during inspiratory pressure threshold loading at 60% P_{Imax}, but not at other loads. Future research is needed to determine whether activation of the metaboreflex during IMT is obligatory for increasing the threshold for activation after IMT.

Conflict of Interest

AKM declares a beneficial interest in the POWERbreathe® inspiratory muscle trainer in the form of a share of license income to the University of Birmingham, as well as acting as a consultant to HaB International Ltd. LAG has no potential conflicts of interest.

REFERENCES

1. Black, L.F., and R.E. Hyatt. Maximal respiratory pressures: normal values and relationship to age and sex. *Am Rev Respir Dis*. 99:696-702, 1969.

2. Brown, P.I., G.R. Sharpe, and M.A. Johnson. Inspiratory muscle training reduces blood lactate concentration during volitional hyperpnoea. *Eur J Appl Physiol*. 104:111-117, 2008.

3. Chiappa, G.R., B.T. Roseguini, P.J. Vieira, C.N. Alves, A. Tavares, E.R. Winkelmann, E.L. Ferlin, R. Stein, and J.P. Ribeiro. Inspiratory muscle training improves blood flow to resting and exercising limbs in patients with chronic heart failure. *J Am Coll Cardiol*. 51:1663-1671, 2008.

4. Dall'Ago, P., G.R. Chiappa, H. Guths, R. Stein, and J.P. Ribeiro. Inspiratory muscle training in patients with heart failure and inspiratory muscle weakness: a randomized trial. *J Am Coll Cardiol*. 47:757-763, 2006.

5. Eastwood, P.R., D.R. Hillman, and K.E. Finucane. Ventilatory responses to inspiratory threshold loading and role of muscle fatigue in task failure. *J Appl Physiol*. 76:185-195., 1994.

6. Geddes, E.L., K. O'Brien, W.D. Reid, D. Brooks, and J. Crowe. Inspiratory muscle training in adults with chronic obstructive pulmonary disease: An update of a systematic review. *Respir Med*. 2008.

7. Gollnick, P.D., R.B. Armstrong, C.W.t. Saubert, K. Piehl, and B. Saltin. Enzyme activity and fiber composition in skeletal muscle of untrained and trained men. *J Appl Physiol*. 33:312-319, 1972.

8. Griffiths, L.A., and A.K. McConnell. The influence of inspiratory and expiratory muscle training upon rowing performance. *Eur J Appl Physiol*. 99:457-466, 2007.

9. Johnson, M.A., G.R. Sharpe, and P.I. Brown. Inspiratory muscle training improves cycling time-trial performance and anaerobic work capacity but not critical power. *Eur J Appl Physiol*. 101:761-770, 2007.

10. Klusiewicz, A., L. Borkowski, R. Zdanowicz, P. Boros, and S. Wesolowski. The inspiratory muscle training in elite rowers. *J Sports Med Phys Fitness*. 48:279-284, 2008.

11. Kraemer, W.J., and N.A. Ratamess. Fundamentals of resistance training: progression and exercise prescription. *Med Sci Sports Exerc*. 36:674-688, 2004.

12. Leblanc, P., E. Summers, M.D. Inman, N.L. Jones, E.J. Campbell, and K.J. Killian. Inspiratory muscles during exercise: a problem of supply and demand. *J Appl Physiol*. 64:2482-2489., 1988.

13. Lomax, M., and A.K. McConnell. Influence of Prior Activity (Warm-Up) and Inspiratory Muscle Training upon Between- and Within-Day Reliability of Maximal Inspiratory Pressure Measurement. *Respiration*. 2009.

14. McConnell, A.K., and M. Lomax. The influence of inspiratory muscle work history and specific inspiratory muscle training upon human limb muscle fatigue. *J Physiol*. 577:445-457, 2006.

15. McConnell, A.K., and L.M. Romer. Respiratory muscle training in healthy humans: resolving the controversy. *Int J Sports Med*. 25:284-293, 2004.

16. Romer, L.M., and A.K. McConnell. Specificity and reversibility of inspiratory muscle training. *Med Sci Sports Exerc*. 35:237-244, 2003.

17. Romer, L.M., A.K. McConnell, and D.A. Jones. Effects of inspiratory muscle training upon time trial performance in trained cyclists. *J Sports Sci*. 20:547-562, 2002.

18. Sheel, A.W., P.A. Derchak, B.J. Morgan, D.F. Pegelow, A.J. Jacques, and J.A. Dempsey. Fatiguing inspiratory muscle work causes reflex reduction in resting leg blood flow in humans. *Journal of Physiology*. 537:277-289, 2001.

19. St Croix, C.M., B.J. Morgan, T.J. Wetter, and J.A. Dempsey. Fatiguing inspiratory muscle work causes reflex sympathetic activation in humans. *J Physiol*. 529 Pt 2:493-504., 2000.

20. Tong, T.K., F.H. Fu, P.K. Chung, R. Eston, K. Lu, B. Quach, J. Nie, and R. So. The effect of inspiratory muscle training on high-intensity, intermittent running performance to exhaustion. *Appl Physiol Nutr Metab*. 33:671-681, 2008.

21. Volianitis, S., A.K. McConnell, and D.A. Jones. Assessment of maximum inspiratory pressure. Prior submaximal respiratory muscle activity ('warm-up') enhances maximum

inspiratory activity and attenuates the learning effect of repeated measurement. *Respiration*. 68:22-27, 2001.

22. Volianitis, S., A.K. McConnell, Y. Koutedakis, L. McNaughton, K. Backx, and D.A. Jones. Inspiratory muscle training improves rowing performance. *Med Sci Sports Exerc*. 33:803-809., 2001.

23. Witt, J.D., J.A. Guenette, J.L. Rupert, D.C. McKenzie, and A.W. Sheel. Inspiratory muscle training attenuates the human respiratory muscle metaboreflex. *J Physiol*. 584:1019-1028, 2007.